A Behavioral Model of Hurricane Risk and Coastal Adaptation

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Abstract

Studies of households have shown a poor perception of natural disaster risks and potential disaster severity, typically overreacting to a disaster event but underpreparing and underinsuring after periods of quiet. Many estimates of disaster response and their economic impacts haven't taken these sub-optimal household perceptions into consideration. Here I build a model of a coastal community to understand how household perceptions are important to modeling a particular natural disaster, hurricanes. "Population Overcrowding" and "Household Motivation for Insurance" are shown to be important feedbacks to the model, necessary to understanding the data. Overcrowding of a community because of limited housing discourages population and inhibits economic growth. A household's desire to insure against a disaster drives insurance coverage, though their desire wanes after several years. While the behavioral decision-making literature and other studies support the relationships between model variables, the model process identified important gaps in the data, suggesting directions for future empirical work.

1 Introduction

Communities respond to natural disasters in a variety of ways. Forest fires, tropical storms, and earthquakes destroy property, devastate local ecosystems and disrupt the social connections. The loss of life and property provide motivation to examine how communities prepare and how responses can lead to better or worse risk mitigation over time. This study examines the dynamics of community response to a disaster and pays particular attention to the perceptions of households of natural disaster risks. Risk perception is a fundamental driver of community response and, to examine the connections between risk perception and disaster response, a coastal community simulation model has been developed.

Studies of disaster response have yielded important insights on how households perceive risk. When looking at the response to hurricanes Hugo and Andrew, researchers discovered residents did not perceive the risk of staying as life threatening (Riad et al., 1999). The result is that nearly 60% of community residents did not evacuate when alerted to the impending storms.

Reluctance to avoid an impending natural disaster is a common global phenomenon. Zhai and Ikeda (2006) report that, in Japan, households often do not respond to flood evacuations because they feel the temporary relocations are inconvenient and they will incur financial costs. The reported inconveniences included the lack of food availability and the poor conditions of emergency shelters.

The inconvenience of evacuation might lead property owners to take protective measures to reduce the damage to their homes, making them more resistant to the natural hazard. Instead, research shows that risk mitigation measures are rarely enacted. Studies of flooding (Kunreuther, 1978) and earthquakes (Drabek et al., 1983) conclude that households do not often take protective measures, such as reinforcing buildings or buying insurance, to prepare for the event.

The data show that households and property owners do take some protective actions. Immediately after a natural disaster, insurance coverage against the disaster rises (Powell, 2007; Stuckey, 2007). The reactionary response to the hazard agrees with risk analysis and decision-making literature – perception of the risk motivates evaluating options and taking action. In this case, the "availability" of a disaster changes the perceived risk of the disaster occurring (i.e., the availability heuristic in Tversky and Kahneman (1974)).

Kunreuther et al. (2001) provide further explanation, reporting that a plausible scenario of a risk motivates people to take protective measures. Recent storm or flooding events provide a tangible scenario to motivate action. Studies of river flooding in Germany further conclude that a statistical decision model that incorporates emotional responses improves the accuracy over a model that simply includes rational expected value decision rules (Grothmann and Reusswig, 2006).

Importantly, the data show that reactionary protection measures remain at an elevated level for a relatively short amount of time. As mentioned, insurance coverage rises dramatically after an event, but falls to its previous level of coverage within 5-10 years. As the "availability" of the event fades and property owners become habituated to the level of risk they face, insurance coverage drops leaving the community under-protected from the economically optimal level.

Both private and public sectors of communities fail to adequately mitigate the risk of natural hazards. Examples of inadequate mitigation include the low level of insurance coverage held by property owners and poor public defense structures, such as levees and seawalls. Poor risk mitigation leads to unnecessary economic losses and larger government expenditures on disaster relief (Kunreuther and Pauly, 2006). A simulation model of the risk perception and disaster response could help decision-makers understand the complex dynamics and design better public policy.

This study combines the aspects of these previous studies into a simulation model of a hurricane-prone coastal community. The model illustrates the feedbacks between risk perception and economic conditions in the wake of a hurricane. The next section of this paper describes the model in detail. Section Three builds intuition of the model's behavior by describing 'reference scenario' results. Section Four highlights the important feedbacks of the model and demonstrates how the results would change if the feedbacks were not included. A discussion of the overall results concludes the paper.

2 Model Description

The model represents a theoretical coastal community. The community has a local economy consisting of Households and an Insurance Market. Within the economy, the actions of households influence the actions of the insurance industry, and vice versa. Additionally, the model has a simple hurricane event module that regulates when a disaster event occurs.

The model's time horizon is 100 years, allowing feedbacks with long time constants to respond. For example, the rate capital stock turnover for the community is slow ($\sim$30 years), requiring a long time horizon to see the capital stock response to storm events. The 100-year simulation time also provides an opportunity to simulate rare events. With the model, we examine a large tropical storm, one that could be considered the hundred-year event for a particular community. The simulated hurricane occurs at a predefined time (i.e., half way through the simulation) and lasts for a short length of time. The model is in dynamic equilibrium before the storm shocks the system, isolating the response to the storm.

The model consists of continuous differential equations following system dynamics methodology (Sterman, 2000). There are four main components or sub-models: 1) Storm Events, 2) Economic Growth, 3) Household Protection Motivation, and 4) Household Protection Choices. The sub-models are self-contained and can be activated or deactivated for different scenarios. Each component contains parameters that were defined as well as possible by existing literature. The model structure and the component interactions are illustrated in Figure 1 and are described further below.

2.1 Storm Events

Storm events are an important driver of the model, affecting each of the other sub-models. The amount of storm damage changes insurance pricing (i.e., a temporary increase in the insurance price) and increases the public awareness of hurricanes. Changes to public awareness drive the Household Motivation for Protection component of the model, which represents how households form the impetus for taking protective actions.

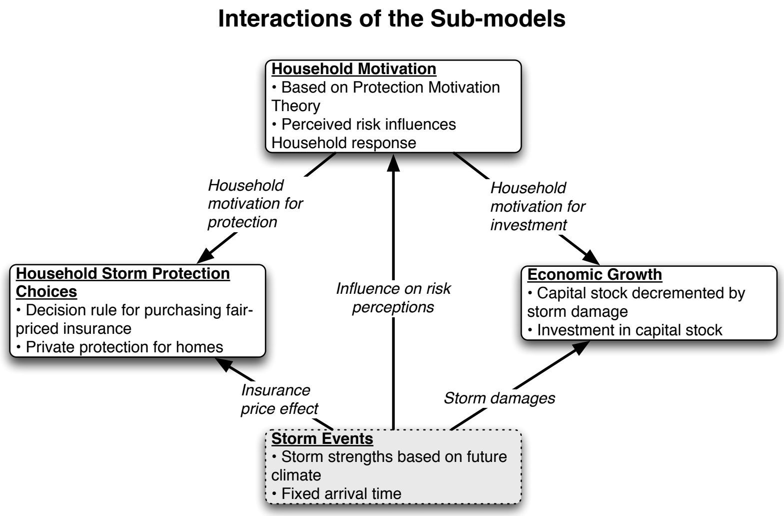


Figure 1: A high-level diagram of the model, including the four components and the information interchanged.

Storm events also cause damage to the community's capital stock. Capital stock is represented as an aggregated variable containing both commercial and household infrastructure. The hurricane event depletes the stock by a predefined amount, averaged from historic large storms. The community's capital stock is important for supporting the current population (i.e., housing stock described below) and for future economic growth.

2.2 Economic Growth

The basis of the economic sub-model is a classic Cobb-Douglas labor and capital production function. Economic output of the community is a function of the capital stock and the labor force:

$$Y = f(K, L) = a(K^{\alpha_k} L^{\alpha_l}) \tag{1}$$

where K is the capital stock, L is the labor force, and α_k and α_l are the shares of capital and labor. Economic output assumes constant returns to scale, so α_k is $1 - \alpha_l$.

If either the capital stock or labor supply grows, economic output increases. Capital stock growth is a function of new capital investment. The model assumes a constant fraction of economic output is invested, based on historical macroeconomic trends, but then changes the investment amount to reflect recent hurricane events. The desired amount of investment decreases immediately after a hurricane because households are fearful of building in the community. Investment returns to historical rates as households become less wary of hurricane risk.

Labor is a constant fraction of the community's population, which can be considered the working age population. The community's population is determined by both exogenous birth and death rates along with endogenous immigration and emigration rates. The net of these four flows is the change to the community's population. Immigration and emigration are endogenous based on the supply of housing capital. Other "community attractiveness" factors, such as job availability and social networks are not currently included in the model (see the Discussion for more details).

Housing capital is important to supporting the community's population, providing residents with affordable and uncrowded homes. In the model, housing capital is a constant fraction of total capital stock. The supply of housing capital determines the relative attractiveness of the community, in important factor in determining where households choose to live. If the community is highly attractive, then immigration will increase and emigration will decrease, reflecting a real-world household choice. If there is a shortage of housing that lowers relative attractiveness, such as immediately after a hurricane when the capital stock declines, then immigration decreases and emigration increases.

2.3 Household Protection Motivation

The community's concerns about storm risk influence choices about future capital investment and disaster preparation. The Household Protection Motivation sub-model represents the important behavioral feedback between storms and these decisions. The sub-model formulation is derived from Protection Motivation Theory (PMT), a psychological theory about how individuals perceive risk and take protective actions. (Maddux and Rogers, 1983; Floyd et al., 2000) When an individual is faced with a risk, they evaluate the risk and their possible courses of actions. The PMT framework splits the decision-making process into three phases: 1) risk appraisal, 2) adaptation appraisal, and 3) avoidant maladaptation. In the first step, the individual evaluates the severity and the likelihood of the risk based on their perceptions. During adaptation appraisal, possible actions are evaluated based on the individual's beliefs about their options to intervene in the system. Finally, given their perception of risk and their analysis of their possible actions, individuals may actually perceive themselves as helpless and/or act in a manner that actually makes the risk worse, called "maladaptation". The outcome of these three processes provides a basis for understanding a household's desire to take protective measures. Household Motivation for Protection (HMP; see Equation 2) is an important input into three areas: insurance coverage, private protection, and capital investment.

$$HMP = (\frac{RA}{RA_0})(\frac{AA}{AA_0})(\frac{AM}{AM_0}) \tag{2}$$

where RA is the household's Risk Appraisal, AA the Adaptation Appraisal, and AM is Avoidant Maladaptation. RA_0, AA_0, and AM_0 are reference values based household risk aversion used to normalize.

Other decision models than PMT could be used to describe household motivation. Rational choice theory would describe households that fully understand their exposure to storms. They would then evaluate each of their protection options, choosing the option that maximizes their expected utility. This study's simulation model doesn't include a rational choice theory model, instead choosing a model that appears to better explain real world behavior of households (e.g., Kunreuther et al., 2001; Grothmann and Reusswig, 2006).

2.4 Household Protection Choices

In second step of the Protection Motivation Theory, households evaluate their protection or adaptation options. The simulation model provides two protection measures: storm insurance and physical protection. When deciding which, if either, of these actions to take, households examine their economic budget constraints. The household insurance decision is based on the relative cost of hurricane insurance along with their perception of the risk of hurricanes. If the cost of insurance is high relative to their exogenous insurance budget, then they are less likely to buy hurricane insurance. An opposing force is their risk perception. If households perceive the risk of hurricane damage to be greater than a background level, then they are more inclined to purchase insurance as a means of financial protection.

Households also can protect themselves with physical private protection. Private protection, such as raising a house on stilts, provides protection to a particular household without providing protection to its neighbors. Such protection protects a particular home from hurricane storm surge, but not the houses that haven't been elevated. The amount of Private Protection purchased by households is decided by the cost of private protection relative to the price of insurance. Households will choose insurance over private protection if insurance is cheaper. Private protection has feedback to the household's risk exposure, reducing the expected insurance losses, thereby reducing the price of future insurance policies.

Endogenous	**Exogenous**	**Excluded**
Immigration rate	Birth rate	Insurance market restructuring
Emigration rate	Death rate	Government disaster relief
Private protection	Time of storm event	National economy
Household motivation	Hurricane damage	
Price of insurance	Insurance losses	
Economic growth		

Table 1: The important endogenous, exogenous, and excluded variables of the model.

The model has several important endogenous and exogenous inputs, listed in Table 1. As described above, many of the behavioral decisions, such as protection choice, are endogenous to the model. The model assumes an average national economic growth rate, excluding the overall national economy from the model. Excluding the larger economy focuses the research on the dynamics within a coastal community. For the US, it is a reasonable assumption that a single natural disaster will not affect the national growth rate significantly.

3 Results

The behavior of the model follows from the structure described above. This section presents the results of the model in two sections. The first contains the results of important variables using three different sets of reference (i.e., default) parameter values. These results build intuition about the behavior of the hurricane adaptation system. The second results section isolates two of the important social feedbacks, showing their importance to model behavior.

3.1 Reference Scenario Results

The reference scenario results can be divided into three main areas: 1) perception issues in response to the hurricane event, 2) household protection actions, and 3) economic effects. Perception issues include how hurricane memories change household motivation for protection. The household protection actions section discusses the construction of private protection and the purchasing of hurricane insurance. Households chose their actions based on the relative prices and their household budget. The economic effects of a hurricane include impacts to economic output and the damage to the capital stock.

Three different model scenarios are used to show the community's dynamics. The first two scenarios, "Storm" and "No Storm", are similar except for the occurrence of a storm event during the simulation. Both scenarios have endogenous economic and population growth. The third scenario, "No Storm, No Growth", deactivates endogenous growth of the community. This scenario serves as a baseline when examining capital stock and population dynamics. All scenarios are initialized with similar values.

3.1.1 Perception Responses to the Hurricane

Household motivation for protection, as described above, is the result of households evaluating the risk of a hurricane event. If an event is salient, then households perceive the risk as more likely. The elevated risk perception (i.e., fear) immediately after a hurricane event motivates households to take protection actions.

Willingness to purchase insurance is an example of households responding to a salient event. Figure 2 shows that after the hurricane event, the change in household motivation for protection would increase the sales of insurance policies $\sim$5X, all else being equal. The effect wanes as households become more accustom to the risk and the memories of the hurricane fade. The model has been calibrated to historic earthquake insurance coverage (Advisen, 2005), a similar natural disaster risk

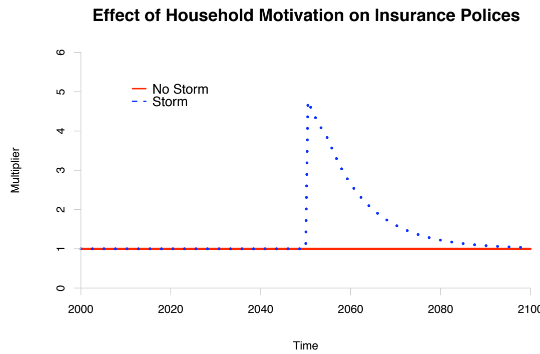


Figure 2: The interest of households to purchase insurance following a hurricane event.

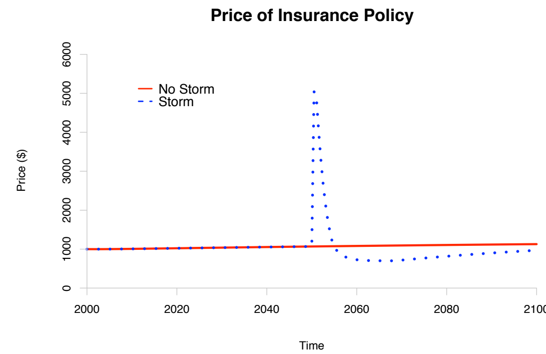


Figure 3: The response of insurance premiums after a hurricane event.

facing households. If no storm occurs, then the motivation to purchase insurance never elevates and remains constant.

3.1.2 Household Protection Choices

The economic markets also respond immediately after a hurricane. Insurance companies try to recover some of their losses by increasing their premiums ∼4-5X (Stuckey, 2007) after a large natural disaster (Figure 3). Slowly the premiums fall as companies reset their prices to the fair-market price, matching competing insurance companies. This temporary price spike, though, discourages the purchasing of insurance by households who have a fixed budget. All things being equal, insurance coverage would fall after a storm. In the "Storm" scenario, the household's motivation to buy insurance (i.e., protect) and the price of insurance effect are counter-balancing forces. The motivation for protection effect dominates, causing a temporary increase in overall insurance coverage (Figure 8; discussed further in Section 3.2).

At the beginning of the simulation, private protection coverage (i.e., the percentage of protection measures implemented) is slowly decreasing. The decrease reflects the choice of new households who buy insurance instead of private protection, if they protect at all. When the storm strikes, households are motivated to build new protection and the coverage increases significantly (Figure 4). This increase is driven both by the high price of insurance and the increased perception of storm risk. Afterwards, these two drivers fade to their previous levels. Private protection decreases driven by the relatively lower price of insurance. If a household chooses to protect itself, it is more likely to buy the cheaper insurance. The slow decline of private protection reflects the long lifetime of the protection, parameterized at 50 years. The price of protection is initialized to be the same price as storm insurance.

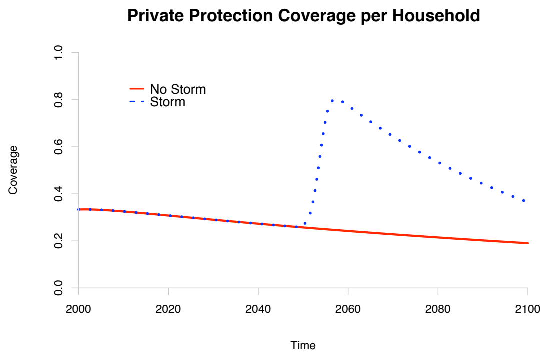


Figure 4: The amount of private protection in the community during the simulation.

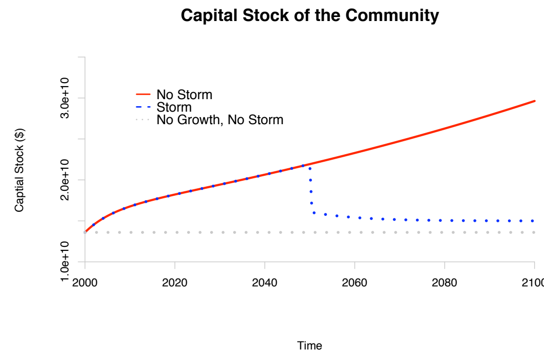
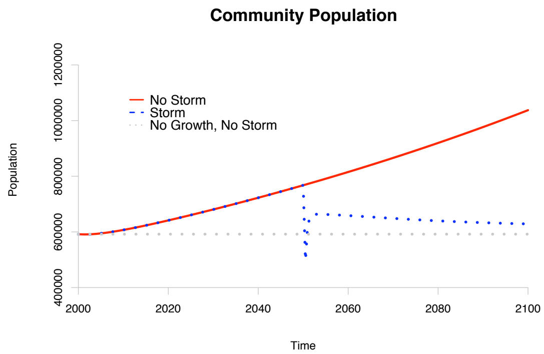


Figure 5: The amount of Capital Stock in the community, depleted by a hurricane event.

3.1.3 Economic Effects

The capital stock grows strongly until the simulated hurricane event. Before the hurricane, new capital investment follows recent trends in community GDP growth, such that the level of desired investment is always met. (Capital investments try to stay apace with overall economic growth.) When the hurricane event occurs, 30% of the capital stock is depleted (Figure 5). A decline in the capital stocks causes a corresponding decline in the housing capital stock, which is a constant fraction of total capital. The capital stock never recovers after the storm. The recovery is hindered by the smaller labor force and the lower capital endowment. Labor and capital are the factors of production for economic output, which determines future capital investment, forming a positive economic feedback in the model. Lower labor and capital levels decreases economic output slowing investment for new capital. Without new capital, the housing stock that supports the labor force is never built.

The community's population increases exponentially before the hurricane event. Immigration is greater than emigration and the housing capital stock grows sufficiently for the new residents, preventing crowding. Immediately after the hurricane, there is a dramatic fall in population because of mass evacuation (Figure 6). Many households return home from evacuation within the first few months, though some choose to resettle elsewhere. After the hurricane, housing in the community becomes crowded and other communities become relatively more attractive. The change in relative attractiveness caused by the housing crunch slows long-term population growth because immigration drops below emigration. The reduction in available labor causes lowers overall economic output and capital investment relative to the "No Storm" scenario. Without capital investments in the housing capital stock, population growth will remain low.



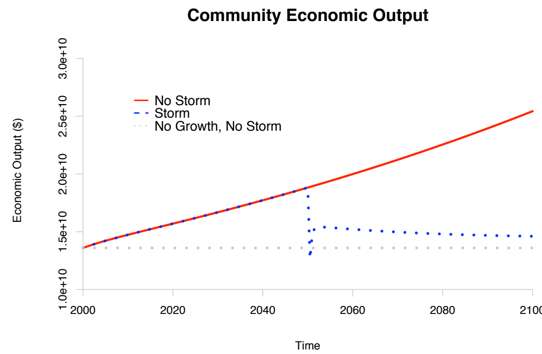


Figure 6: The Population of the community, which is the net change of immigration, emigration, evacuation, returning, births, and deaths.

Figure 7: The economic output (GDP) of the community.

The gross output of the economy is a function of capital and labor. Driven by population growth and a growing capital stock, output has strong growth until the storm. Economic output drops sharply immediately after the storm because of the capital damage and the displacement of labor (Figure 7). Because of the capital and labor dynamics described above, economic output remains low for the remainder of the simulation.

3.2 Importance of behavioral feedbacks

This section highlights the importance of two model feedbacks by comparing output to the "Storm" scenario described in the previous section. Behavioral feedbacks are parameter relationships that capture the human-agency aspects of hurricane resonse. As described in Section 1, coastal residents respond to a disaster based on past experiences and risk perception.

The first important behavioral feedback in the model is between risk perception and insurance coverage. The household motivation for insurance feedback captures the increase in household motivation to take protective action immediately after a storm event. The motivation for protection can be seen by the increase in insurance coverage. Turning the feedback off causes insurance coverage to fall after the hurricane event (Figure 8). The fall in coverage is due to increase in the price of insurance relative to the fixed household budget for insurance without the offsetting behavioral desire for protection. Motivation counteracts the higher insurance price, increasing total coverage relatively quickly after the storm. The feedback between risk perception and protective actions is important to understanding real-world phenomenon (Advisen, 2005), including the drop-off of insurance coverage as the "availability" of the disaster wanes.

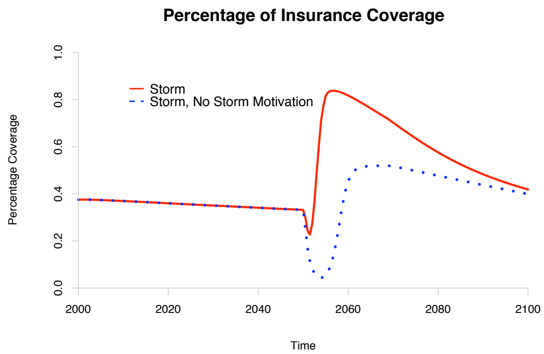


Figure 8: The response of Insurance Coverage with and without the Household Motivation for Insurance feedback.

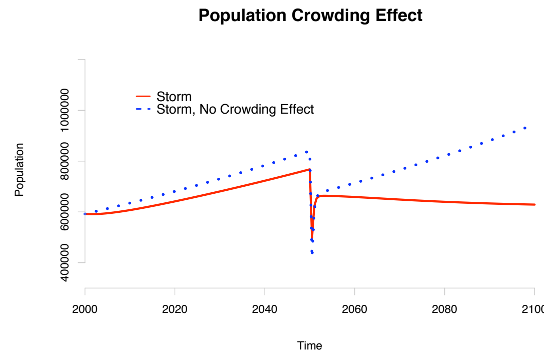


Figure 9: The Population of the community with and without the "overcrowding" feedback of the Housing Stock.

Another important feedback is "population crowding", which reflects how a community's relative attractiveness is based on its occupancy rate. A high occupancy rate could be because of too many people or too little housing. In the "Storm" scenario above, the crowding feedback is active and the population and economic output drop after the hurricane, remaining low. Figure 9 shows the behavior of the model when the relative attractiveness of the community doesn't depend on housing. Without the feedback, population grows more quickly. During the hurricane, some of the population is displaced, but afterwards many return and the population continues to climb exponentially. Without the crowding feedback, economic output is also higher because of the larger labor force in the community.

4 Discussion and Conclusion

Natural disasters send a ripple of cause and effect through a community. Lives are disrupted and property is destroyed. This research examines the dynamics of the disruption by combining physical and economic damage along with psychological effects into an integrated simulation model. By highlighting some of the important social feedbacks, such as "population crowding" and "household motivation to buy insurance", this research demonstrates that social feedbacks are important to understanding community response to natural disasters. Isolating these effects in real-world data is difficult but it appears, from the aggregation of natural disaster reports and studies, that the model behavior with the feedbacks is more accurate that the behavior without. Psychological and behavioral feedbacks are important to understanding the hurricane response system.

The model makes simplifications and includes subjective judgment where it was difficult to find solid studies. Improvements to these assumptions could change the values of the results, but the overall dynamics would remain unchanged. A good example is Household Motivation for Protection. Changing the sensitive inputs parameters to household motivation produces similarly shaped curves over the simulated period. For this research, the fundamental sign of the parameter correlation (i.e., positive or negative) is critical. Several studies have demonstrated the sign of household motivation for protection (e.g., Grothmann and Reusswig, 2006; McClure et al., 1999) and this research includes their correlation.

Data regarding insurance company pricing and behavior were expected to be plentiful but were hard to find. Anecdotal evidence provides a starting point for parameter relationships, but no rigorous data analysis has yet been discovered. Data about premium response before and after a storm likely exist, but may be internal to insurance companies. These data are important to modeling the price spike after a storm event and determining the time constants of the price increase and the subsequent decrease.

A fundamental problem with simulating a US natural disaster is the representation of government intervention. After a large event, FEMA and other Federal agencies provide medical, financial, and logistical assistance. The financial assistance, in particular, injects the local economy with new capital faster than represented in the current model. Another common form of intervention is insurance regulation. Many states cap premiums and their annual adjustments. In several instances, such as after the 1992 California earthquake, the state became the insurance provider, often offering coverage at a discounted rate. These forms of government intervention are hard to model, but are important to understand coastal community response after a tropical storm.

The model is not comprehensive in covering the full range of community dynamics. For example, a community's relative attractiveness is composed of many different factors. In real life, people move to a community for a variety of reasons, including schools, jobs, safety, proximity, affordability, and space. The current model only includes the last element, space, by including a notion of crowding. It is obvious that the attractiveness structure is important to the model, but the inclusion of one factor is a limitation. In the future, attractiveness will have a richer set of contributing factors. These dynamics provide the opportunity for further model improvements and are planned for future work.

The present simulation is a step to having a more integrated picture of the important dynamics between human behavior and unpredictable natural disasters. The simplified simulation model presented in this paper shows that behavioral feedbacks are important to understanding the market and community changes following an event. The ultimate goal of the research is to highlight area of policy intervention, creating more resilient towns and cities.

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